Exercise 10

Tides

OBJECTIVES:

- To understand the roles that gravity and centrifugal force play in influencing the heights of oceanic tides throughout a lunar month.
- To understand why tides arrive at different times and why they display different magnitudes and frequencies in coastal and deep water.
- To understand how the shape of the coastline influences the tides.
- To know what tidal data planes are and why are they important to navigation.

To the casual observer the most obvious change in the level of the sea is that of the tides. They are caused mainly by the moon and the sun exerting forces on different parts of the rotating earth. The tidal wave, or bulge, is the result of *gravitational attraction* and *centrifugal force,* which act in combination to produce a regular variation in water level in the course of a day.

Tide-Producing Forces

Consider only the earth–moon system. Although the moon appears to revolve about the earth, the two bodies are actually rotating about a common center of mass. They are held together by gravity and kept apart by an equal and opposite centrifugal force. Thus, on the side of the earth closest to the moon, the tide-producing force is gravitational, whereas on the opposite side centrifugal force dominates.

We can illustrate this point by showing the water motion resulting from only the horizontal tide-generating forces (Figure 10-1a). When the moon is over the equator, water is drawn by gravitational attraction toward the side nearest the moon, and toward the opposite side by centrifugal force, so that high tides with a low tide belt in between result. Because the forces are of equal magnitude symmetrically about the equator, two high and two low tides of equal magnitude should be experienced, at least in theory, at any given latitude on the earth. As the moon shifts north or south of the equator (that is, when it is at north or south declination), the forces are as shown in Figure 10-1b. A point at the equator is still subject to highs and lows of equal magnitude, but points at higher latitudes will experience strong diurnal inequalities; in other words, they will experience high tides of unequal heights, or perhaps only one high tide.

Tide Levels and Datum Planes

Because the ocean basins vary in size and shape, and because land masses interfere with the tidal bulge, the tides do not assume a simple regular pattern. Although a purely mathematical solution of the tidal phenomenon is still beyond the limits of marine science, it is possible to predict the tide level at least 1 year in advance by careful analysis of tide records from stations at which observations have been made for long periods of time. Most of the averages are based on at least 19 or 20 years of records, and quite accurate prediction is routine.

The tide level is usually measured in reference to a local base level, or **datum** plane, which is an

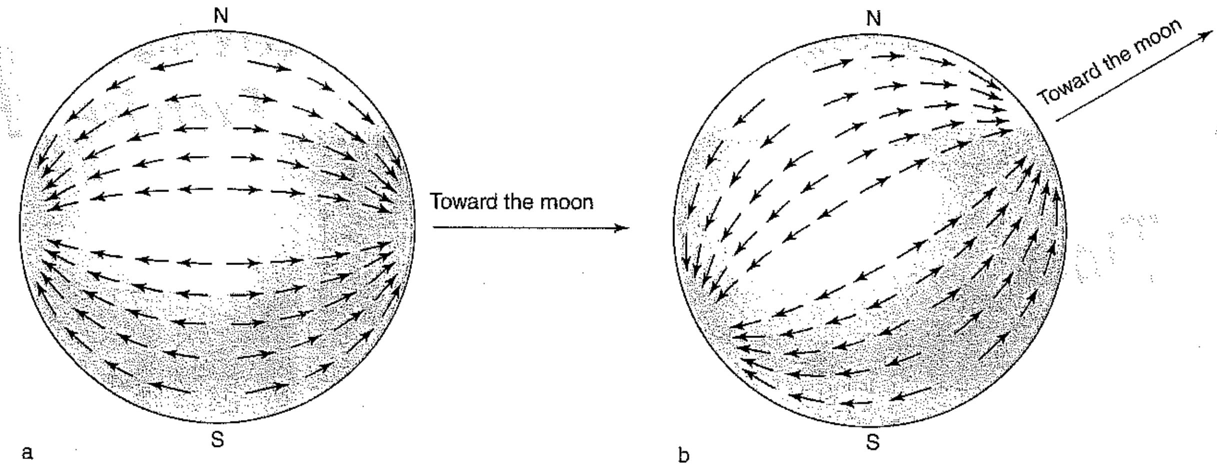


Figure **10-1** Tide-producing forces. The arrows represent the magnitude and direction of the horizontal tide-generating forces on the earth's surface. The force pulling away from the moon is the centrifugal force produced by the rotation of earth and moon about their common center of mass. (a) When the moon is in the plane of the earth's equator, the forces are equal in magnitude at the two points on the same parallel of latitude on opposite sides of the earth. (b) When the moon is at north or south declination, the forces are unequal at such points and tend to cause an inequality in the two high waters and the two low waters of a tidal day. [After N. Bowditch, *American Practical Navigator.* Hydrographic Office Publication No. 9, U.S. Naval Oceanographic Office, 1966.]

average of many years' observations. The typical datum in the United States is mean lower low water (MLLW), which is the average of the lowest tide each day. Another common datum is mean low water (MLW). This is the average of all low-tide levels at the station, but is not as safe a point of reference for navigational purposes as mean lower low water, since at least half of the lows during a month will be lower than the datum. Other datum planes are mean sea level (MSL), mean high water (MHW), and mean higher high water (MHHW). Inasmuch as mariners depend on the charted depths, and since these are established in reference to the tide datum, it is obvious that the best datum will be the lowest normal level that the tide will reach. The relationship between levels of the sea and datum planes for the Orange County coast of California are shown in Table 10-1.

Types of Tides

Three major types of tides can be recognized on the basis of frequency of occurrence and symmetry of the tidal curve. **Diurnal tides** occur once daily, meaning that there is one high and one low tide of about equal amplitude, or height, in the course of a **tidal day.** A tidal day is 24 hours and 50 minutes long because the moon, which exerts the greatest tidal influence, advances 50 minutes each day in its orbit around the earth. **Semidiurnal tides** occur twice daily and are also of about equal height. **Mixed tides,** also known as *irregular semidiurnal tides,* occur twice daily but exhibit two highs and two lows of significantly unequal height. The type of tide that occurs on a given coast and its variation in height depend on a number of factors. Among them are the shape of the basin in which the tide occurs, natural oscillations of the water (seiches) within the basin, declination of the sun and moon, and relative position of the sun and moon. Tides on the East Coast of the United States are representative of the semidiurnal type, whereas those on the West Coast are mixed tides. However, either coast may exhibit both types at certain times of the year. Diurnal tides typically occur in partially enclosed basins such as the northern Gulf of Mexico, the Java Sea, and the Gulf of Tonkin off the Vietnam–China coast (Figure 10-2).

TABLE 10-1

Sea levels and datum planes for the coast of Orange County, California

	Datum mean sea level		*Datum mean lower low water*	
Sea level	**(feet)**	**(meters)**	**(feet)**	**(meters)**
Highest tide	4.8	1.5	7.5	2.3
Mean higher high water	2.6	0.8	5.3	1.6
Mean high water	1.9	0.6	4.6	1.4
Mean sea level	0.0	0.0	2.7	0.8
Mean low water	−1.8	0.5	0.9	0.3
Mean lower low water	−2.7	0.8	0.0	0.0
Lowest tide	−5.2	1.6	−2.5	0.7

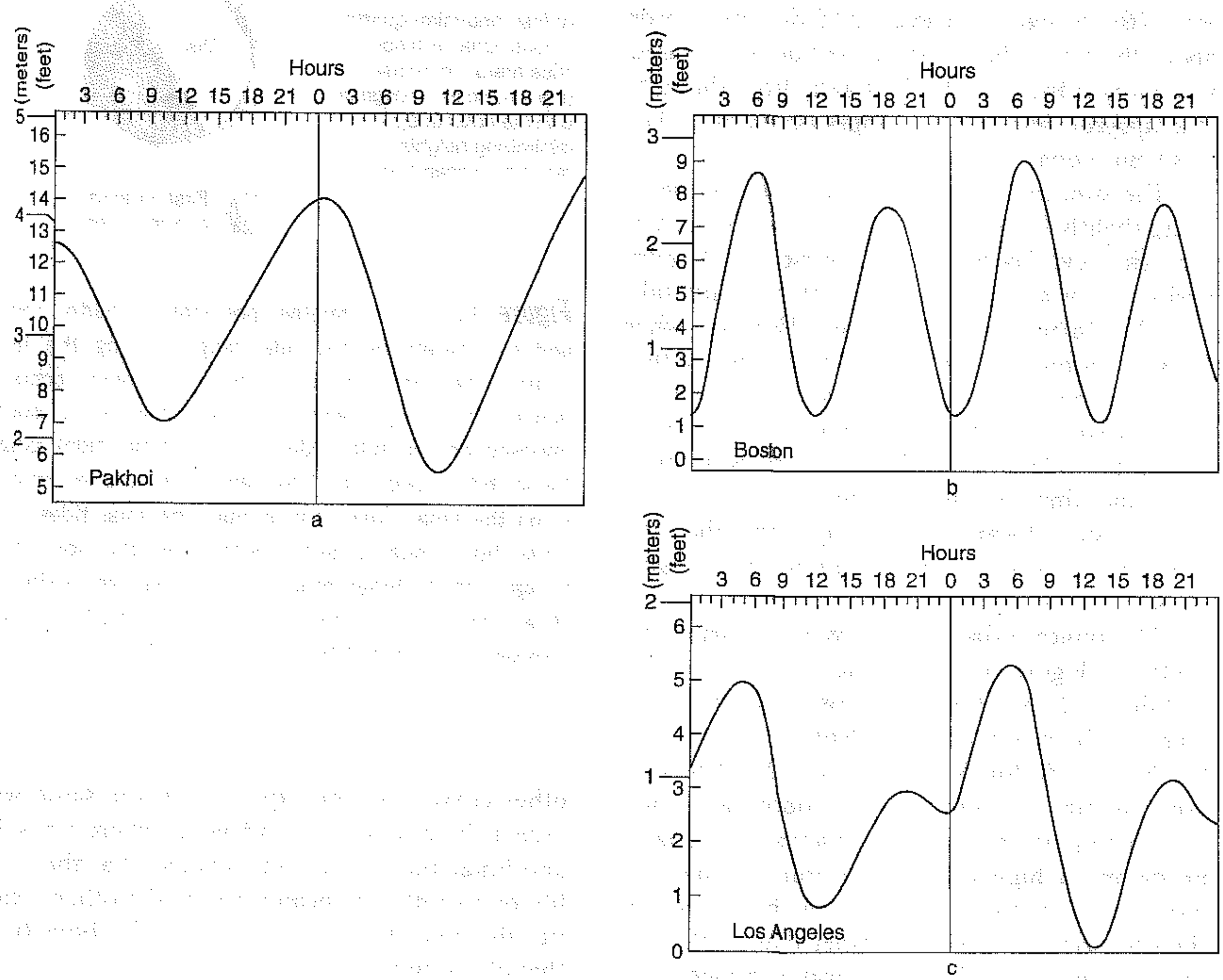


Figure 10-2 Types of tides from the Atlantic and Pacific ocean basins: (a) diurnal type; (b) semidiurnal type; (c) mixed type.

Monthly Tidal Cycles

Tides are also identified by their **tidal range:** those having, in the course of a lunar month, the largest difference in level between high and low are called **spring tides;** those having the smallest range of the month are the **neap tides.** Spring tides occur twice monthly, at or near the time of new moon and of full moon. At these times, tides are at their highest and lowest levels in relation to their mean level. Perhaps the best datum to use for navigational purposes would be the average of all low spring tides or mean lower springs. Neap tides—the tides of lowest range (the lowest high tides and the highest low tides)—are also influenced by the lunar cycle and occur twice a month at or near the first quarter and third quarter phases of the moon (the half moon).

Other fluctuations in the tidal range occur in response to the elliptical nature of the moon's orbit. When the moon is at a point closest to the earth (the *perigee*) once every 27.5 days in its orbit about the earth, the range of the tide is increased; when it is at the point farthest away from the earth (the *apogee*), smaller tidal ranges occur, other factors being equal.

The sun, too, causes tides, the solar influence being slightly less than half that of the moon. The solar tidal cycle occurs in the course of a 24-hour period and is not synchronous with the lunar tidal period of 24 hours and 50 minutes. However, when the sun, moon, and earth are in alignment, as they are at new and full moons (Figure 10-3a,b), the lunar and solar components reinforce one another and spring tides result. When neap tides occur, at first- and third-quarter moons, the sun–earth–moon system forms a right angle and the tide-producing forces are greatly diminished (Figure 10-3c).

The typical tidal curves given for various localities in Figure 10-4 show the three major types of tides and the effects of proximity and alignment of the moon and sun. Note the tidal curve for New York for September 22–26. The tidal range is high because the sun, moon, and earth are lined up; the sun and moon are at the equator, producing a high degree of symmetry, and the moon is at perigee, causing the higher spring tides to occur at this time rather than at the new moon phase when the moon was at apogee. The other curves may be explained in the same way, except the one for Port Adelaide, where the solar and lunar tides are about equal, so that they nullify one another at neap tides (at the other localities the lunar tide-producing force is about twice that of the sun).

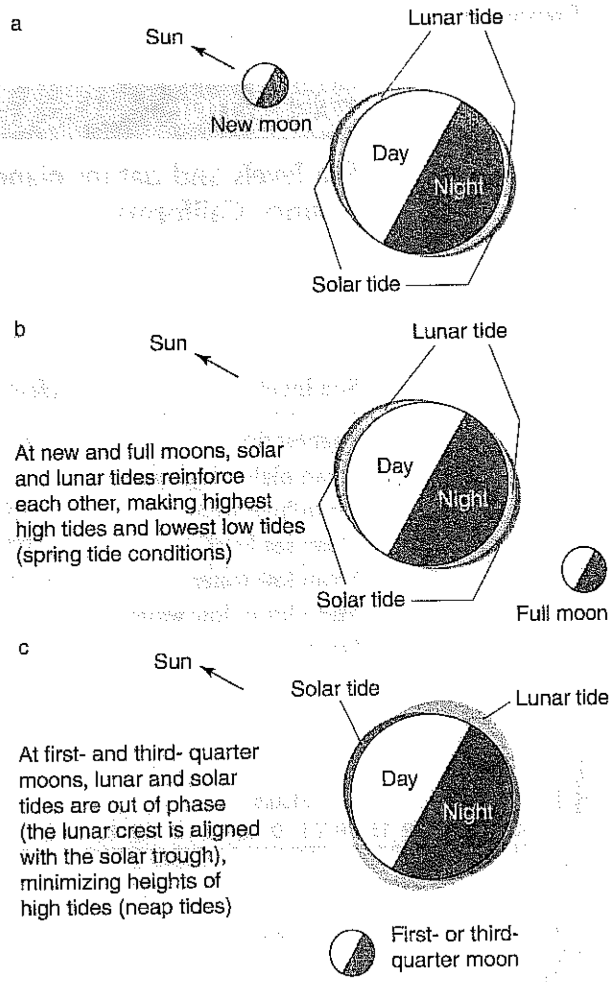
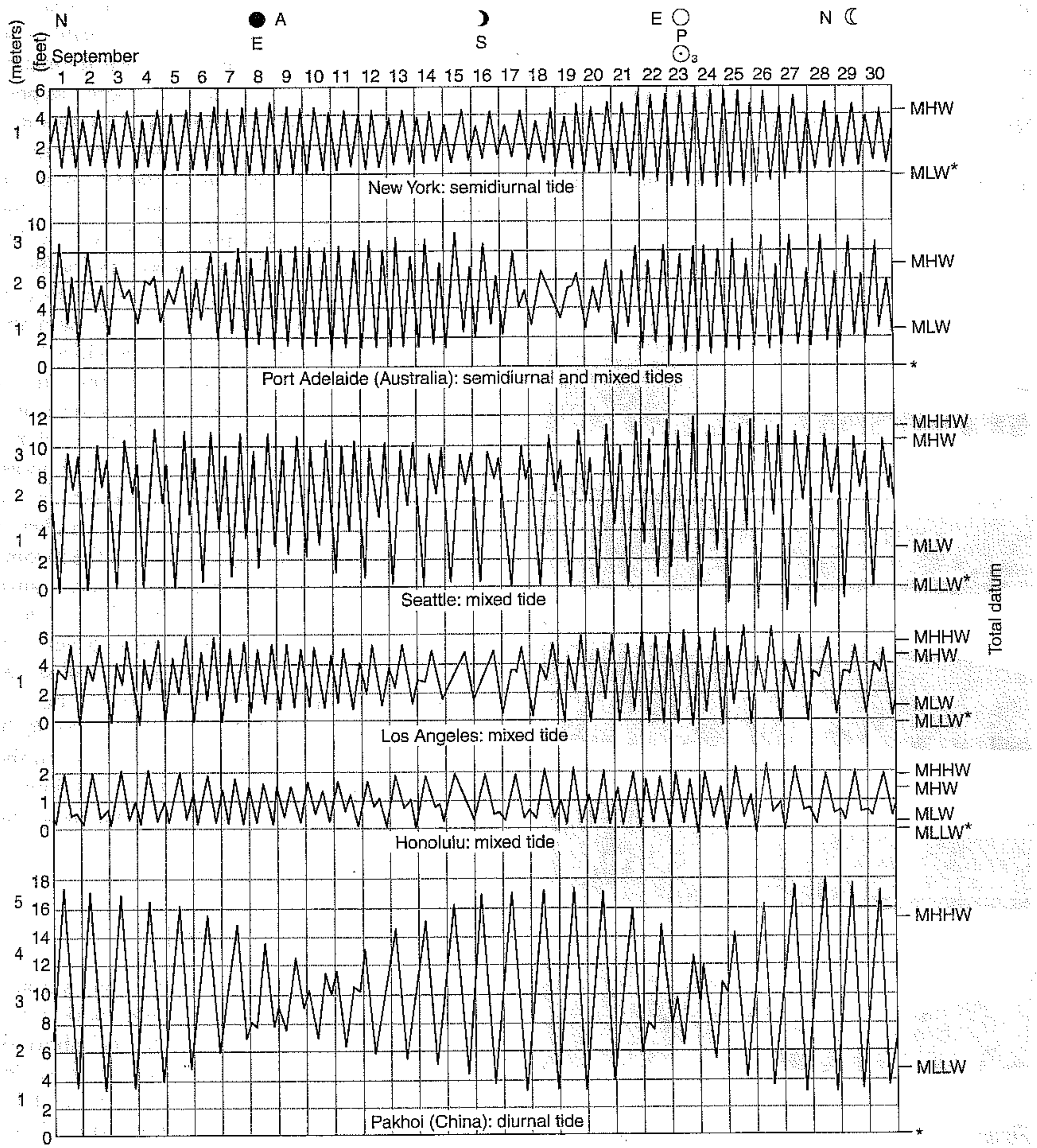


Figure 10-3 The relative positions of earth, moon, and sun determine the tidal ranges during the lunar month. The highest tidal ranges (spring tides) occur at new and full moons, when the lunar tidal crest is superimposed on the solar tidal crest. Minimal tidal ranges (neap tides) occur at first- and third-quarter moons, when the lunar tides "cancel out" the solar tides—the lunar tidal crest is superimposed on the solar tidal trough, and the lunar trough and the solar crest coincide. [After F. Press and R. Siever, *Earth,* 4th ed. W. H. Freeman and Company. Copyright © 1986.]



● New moon
☽ First quarter
○ Full moon
☾ Last quarter
E Moon on the equator
N Moon farthest north of the equator
S Moon farthest south of the equator
A Moon in apogee
P Moon in perigee
$\odot_3$ Sun at autumnal equinox
* Chart datum

Figure **10-4** Examples of tide records for several tidal types. [After N. Bowditch, *American Practical Navigator.* Hydrographic Office Publication No. 9, U.S. Naval Oceanographic Office, 1966.]

Unusual Tides

There are places in the world where tidal ranges exceed 10 meters and may reach as much as 16 meters. These occur in bays or harbors open to the ocean that are very long compared to their depth. Natural oscillations, known as *seiches,* in these basins cause water to slosh back and forth much like the waves you can create when walking with a coffee cup. Physicists refer to these waves as *standing waves,* or *forced oscillations,* because the water stands first high and then low through one cycle. If the fundamental period (one up-down cycle) of the tidal basin or harbor is equal to the Earth's tidal period (12 hours and 25 minutes), then resonance results, and extreme tidal ranges may occur, as positive reinforcement "stacks" the crests of waves resonating in the basin. A simple "desktop" demonstration of resonance can be obtained with an empty soda bottle. Blowing air gently across the open top of the bottle may produce a loud tone due to resonance of the air vibrating inside the bottle.

Figure 10-5 shows the way in which the natural frequency of oscillation of a tidal basin and the tidal frequency may be in phase to produce resonance. This constructive reinforcement creates large tidal ranges—as great as 16 meters in the Bay of Fundy, 10 meters in the upper reaches of the Gulf of California, and 10 meters at Anchorage, Alaska. In some narrow funnel-shaped estuaries a *tidal bore* develops. This phenomenon, an abrupt solitary wave that moves upstream with the incoming tide, can be quite dangerous, since bores range in height from a few inches to as much as 25 feet. The most famous is on the river Severn in England; about 4 feet high, it can pass an observer on the run (Figure 10-6). Bores occur on the Amazon River (up to 25 feet high), on the Knik and Turnagain arms of the Cook Inlet, and on the Petitcodiac River at the head of the Bay of Fundy, also noted for its extreme tidal range during spring tides.

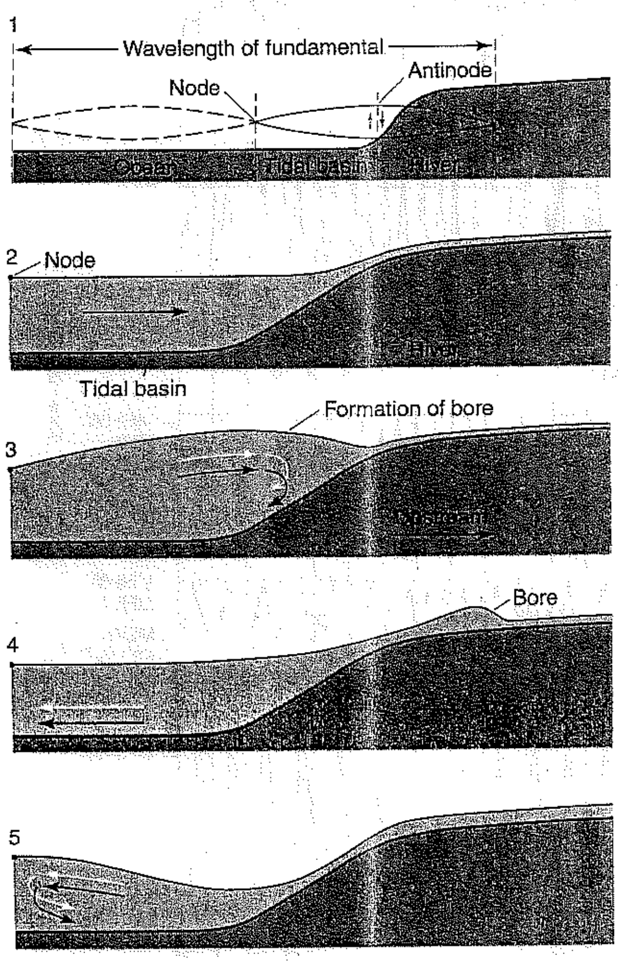


***Figure* 10-5** Oscillation, or seiche, of the water in a tidal basin. The time it takes the standing wave to make one complete oscillation is the fundamental period. The node is a point of little or no vertical movement of water; the antinode is a point of maximum vertical movement of water. If the tide rises fast enough, a bore is formed in the river mouth. The effect of constructive reinforcement, or resonance, is shown in panels 2–5. [After D. K. Lynch, "Tidal Bores." Copyright © 1982 by Scientific American, Inc. All rights reserved.]

Storms and Water Level

In most coastal areas the wind may induce surface-water flow in the direction of wind motion and thus cause the water level to rise or fall above or below that level owing to astronomical tides. The term **wind setup** is used when this effect takes place in a lake or reservoir, and **storm surge** is applied to the same effect along the open coast. It is extremely important for the planning of engineering projects to know how much storm surge can be expected in a coastal area.

For example, storm surge in southern California is predicted to be about 1 m above highest tide levels; therefore engineering works should be constructed at least 3 m above mean lower low water (see Table 10-1). The amount of surge de-

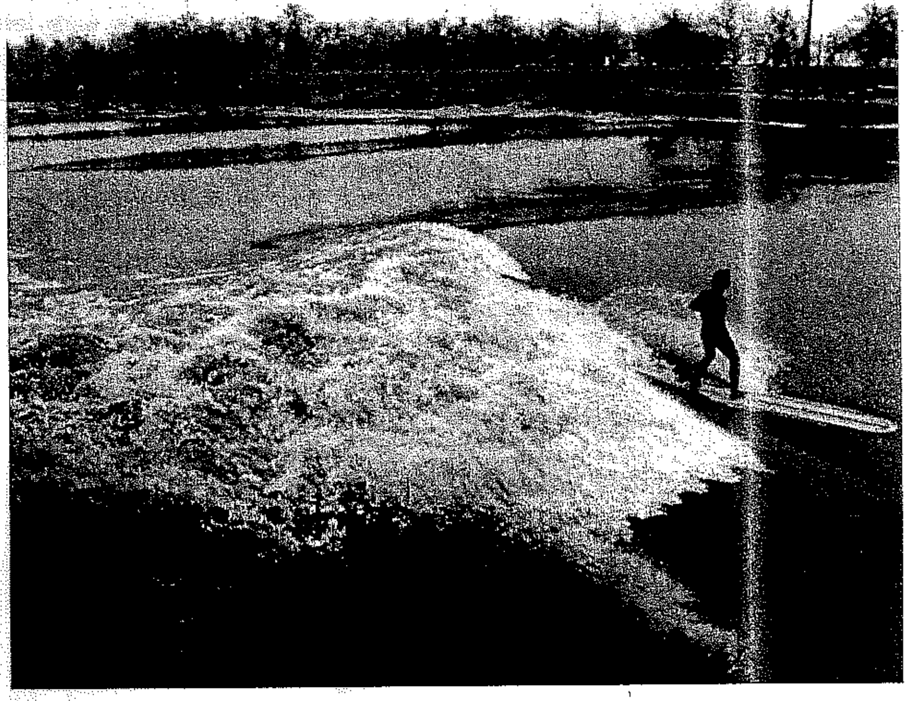


Figure **10-6** Tidal bore on the Severn River is large enough for surfers to ride upstream for miles. [After D. K. Lynch, "Tidal Bores." Copyright © 1982 by Scientific American, Inc. All rights reserved. Photo by C. G. Kershaw, Severn-Trent Water Authority.]

pends on the wind velocity, the length of open sea surface across which the wind can generate waves, and the depth of the water; surge is greater for shallow water. The influence of shallow water is the reason that storm-surge values are higher on the Gulf Coast than on the Atlantic Coast (and on the Atlantic Coast higher than on the Pacific Coast). Indeed, in 1900 a hurricane surge on the Gulf Coast Galveston, Texas, was so high that water levels rose 5 m above mean lower low water, inundating much of the coastal land; and in any year surges of 2–3 m feet above tide levels are not unusual along the southeastern coast of the United States.

Tsunamis and Tides

Tsunamis are impulsively generated waves that can be very destructive. They are generated by movement of the sea floor due to faulting, submarine landslides, or volcanic action. They have wavelengths of 130 to 165 kilometers and travel with velocities of 650 kilometers/hour (400 miles/hour). Their deep-water height is less than 3 meters, and they go unnoticed in the open ocean. However, as they approach the shoreline, their wavelength decreases and their height increases to many tens of meters. They have a very definite signature on tide-gauge records. Figure 10-7 shows the tide-gauge record at various ports for the destructive tsunami of April 1, 1946, in the Pacific Ocean basin. It was generated by subduction of the Pacific Plate under the North American Plate in the Aleutian Trench. The wave sped across the Pacific Ocean and did enormous damage in the Hawaiian Islands and coastal Alaska. Note the sudden "spikes" in the otherwise rather smooth sinusoidal shape of the tide curve.

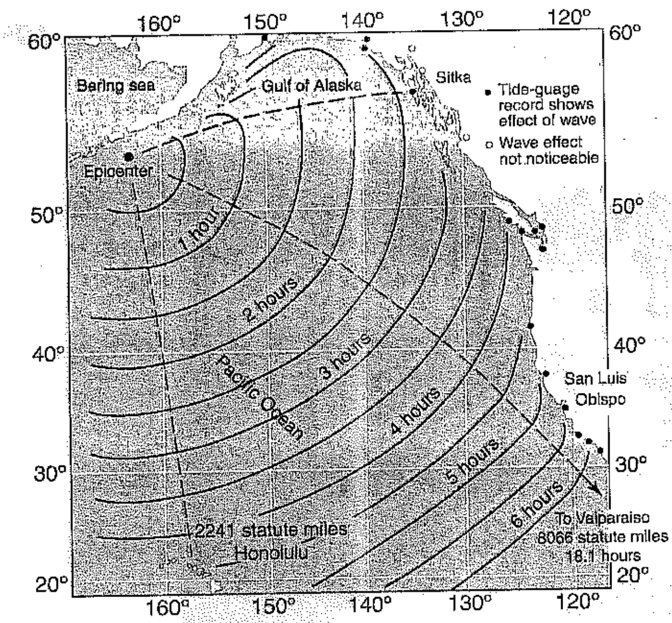
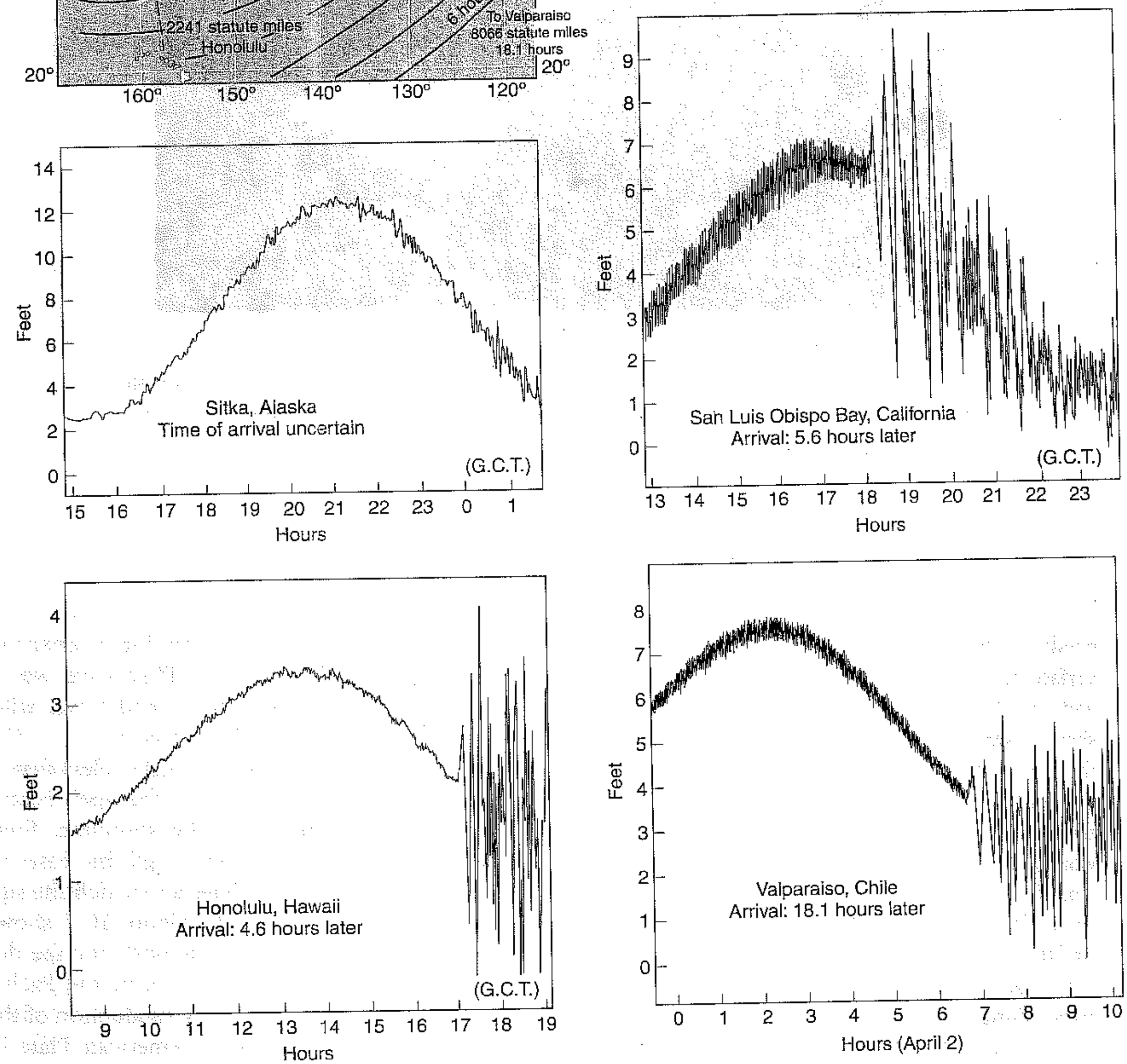


***Figure* 10-7** Records for a seismic sea wave (tsunami) of April 1, 1946, at selected points around the Pacific Ocean. Note that the tsunami arrived at different places at different stages of the tidal cycle, and that the first sign of its approach was a small rise followed by a larger fall in water level. The maximum height was not reached until the third or fourth crest, at least half an hour later. The map summarizes the direction of propagation and rate of travel. [Modified from C. K. Green, *Trans. Amer. Geophysical Union*, 1946.]



DEFINITIONS

Datum. The reference level to which tide levels are compared. The datum planes commonly used are mean low water or mean lower low water, which are the average levels of low tides taken over a 19-year period. These are also the datum planes ("0" ft or "0" m) used in constructing bathymetric charts.

Diurnal tides. Tides occurring once daily, one high and one low tide per tidal day.

Mixed tides. Complex tide curve, usually with two highs and lows of unequal height per tidal day.

Neap tides. The tides of lowest range, occurring twice monthly when the moon is a quadrature (so that the sun and moon are 90° apart).

Semidiurnal tides. Tides occurring twice daily. There are two high and two low tides per tidal day.

Spring tides. The tides of highest range, occurring twice monthly when the lunar and solar tides are in phase.

Storm surge. A rise above normal water level on an open coast due to strong winds blowing onshore. Storm surge resulting from a hurricane or other intense storm also includes the rise in level due to atmospheric pressure reduction as well as that due to the winds. A storm surge is most severe when it occurs in conjunction with a high tide.

Tidal day (or lunar day). The time between two successive transits or passings of the moon over a local meridian. It is derived from the rotation of the earth relative to the movement of the moon about the earth. As the earth rotates once on its axis (24 hours) the moon has advanced in its orbit about the earth about 50 minutes; therefore the tidal day is 24 hours and 50 minutes long.

Tidal range. The difference in height between successive high- and low-tide levels.

Wind setup. The vertical rise in the water level on the leeward, or downwind, side of a body of water due to strong winds. Wind setup is similar to storm surge but the term is usually applied to reservoirs and smaller bodies of water.

Exercise 10

Report

Tides

NAME ______________________

DATE ______________________

INSTRUCTOR ______________________

1. Plot the tide heights at the proper time and day from the harbor tide record on the graph on the following page. Heights in the record are all measured above mean lower low water (MLLW) in the harbor. Connect the points with a straight line to produce a tide curve. Although straight lines do not produce the smooth curves like those shown in Figure 10-2, the record shows tide types and changes.

Harbor Tide Record

Day	Time (24 hour)	Height (meters)	Day	Time (24 hour)	Height (meters)
1	2400 (0000)	1.2	3	0955	1.8
	1130	2.1		1625	1.4
	2200	1.3		2205	1.7
2	0430	2.0	4	0720	1.4
	1110	1.2		1345	2.1
	1815	1.7		2205	1.6
3	0320	1.3		2345	1.8

(a) What type of tide is shown on day 1 __________, day 2 __________, day 3 __________, and day 4 __________?

(b) The least tidal range in the set is __________ meters on day __________.

(c) What is the elevation of the mean high water for the 4 days? __________ meters

(d) The datum for your curves is mean lower low water (MLLW). You have a small sailboat that draws 1.7 meters (5 $\frac{1}{2}$ feet), and you wish to sail it through a passage that is underlain by a rocky reef that is just exposed at MLLW. On what days and at what time would you sail? ______________________

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2. Just before midnight on day 5, the harbormaster noticed some unusual events in the harbor. A more detailed tide record was obtained, which is shown below. Add these points to day 5 on the tide curve of Question 1.

(a) What event is suggested by these supplemental data, and what causes these events to occur?

Day	Time (24 hour)	Height (meters)	Notes
4	2345	1.8	Last regularly scheduled observation
5	0000	1.7	Sudden fall of water in harbor
	0020	3.1	Rapid rise of water
	0035	0.6	
	0048	3.4	Upper limit of tide gauge
	0100	0.2	Tide gauge fails—site abandoned

(b) Which part of the event, the trough or the crest, entered the harbor first? ______

(c) Is this event unusual? If not, how might knowledge of this be of survival value?

3. (a) Using the travel time diagram in Figure 10-7, suggest the time required for a tsunami generated in the Aleutian Trench to arrive at the following locations:

Sitka, Alaska ______
Honolulu, Hawaii ______
San Luis Obispo, California ______
Valparaiso, Chile ______

(b) What is the average velocity of the tsunami between the Aleutian Trench and Hawaii, 3600 kilometers distant? ______ kilometers/hour.

Between the Aleutian Trench and Valparaiso, Chile? ______ kilometers/hour.

Give a possible explanation for this difference in velocity between the two places.

(c) Estimate the greatest height of the tsunami above the tide level when the tsunami arrived at:

Sitka ______ meters
Honolulu ______ meters
San Luis Obispo ______ meters

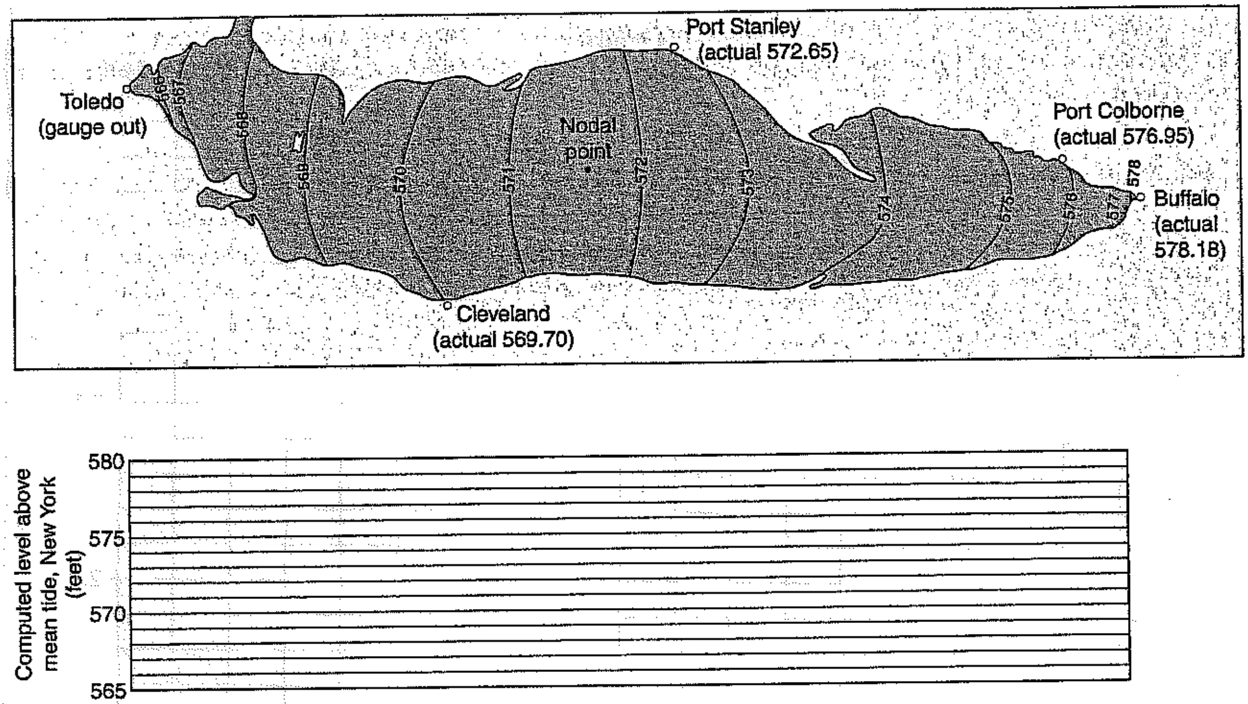


Figure **10-8** Effects of wind on surface-water level of Lake Erie. The contours show the water-level computer at 11:00 P.M. on November 8, 1957. [After I. A. Hunt, Jr., *Winds, Wind Set-up and Seiches on Lake Erie*. U.S. Lake Survey, U.S. Army Corps of Engineers, 1959.]

(d) What was the first evidence of the arrival of the tsunami on the shoreline at Honolulu—was it the trough or crest of the tsunami? ______

What crest in the series did the greatest damage? ______

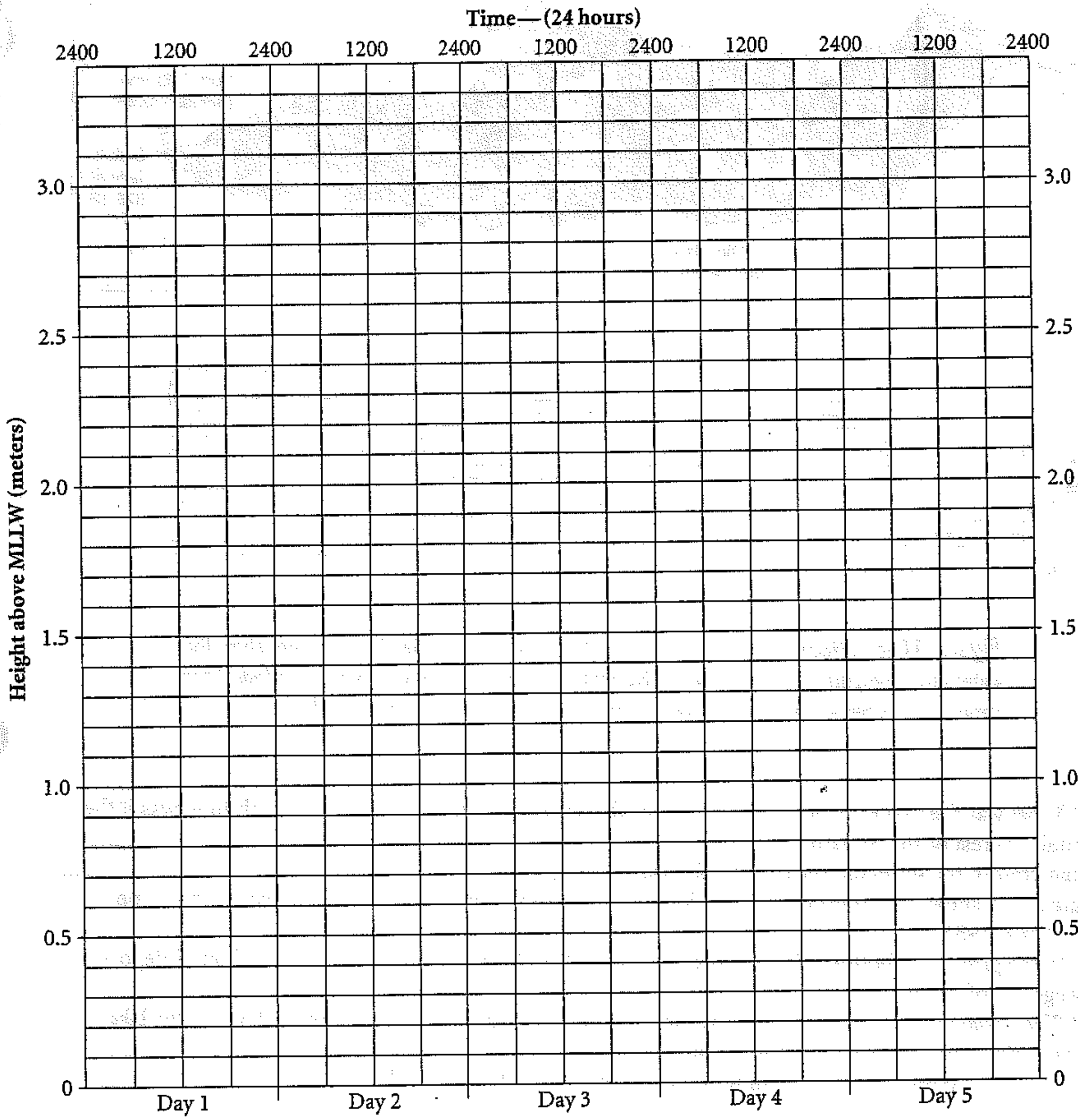
4. Figure 10-8 shows the contours of water levels that were computed on Lake Erie during a storm on November 8, 1957.

(a) In the grid at the bottom of the figure, draw a profile of the computed water levels from Toledo (gauge out of water) to Buffalo.

(b) The nodal point is the point of no vertical change and thus represents the mean level of the lake. What is the value of the wind setup at Buffalo? ______

What is the maximum difference in water level between Buffalo and Toledo? ______

5. In the waters off southern California a small smeltlike fish, *Leuresthes tenuis* (the grunion), exhibits an interesting reproductive strategy finely timed to the tidal cycle. During spring tides from April to August, grunions come ashore shortly after the highest tides (which occur at night), and the female deposits eggs a few inches deep in the damp beach sand. The eggs are then fertilized by male grunions and are ready to hatch in 9–10 days, but only when the tidewater reaches them and they are agitated by surfaction. When will grunion eggs deposited at full moon on July 3 have their first opportunity to hatch? ______


Time—(24 hours)
2400 1200 2400 1200 2400 1200 2400 1200 2400 1200 2400
Height above MLLW (meters)
3.0
2.5
2.0
1.5
1.0
0.5
0
Day 1
Day 2
Day 3
Day 4
Day 5